Design and Analysis of Compact MIMO Antenna with Isolation Enhancement using CMA/Decoupling Techniques

Synopsis of the Thesis to be submitted in Partial Fulfillment
of the Requirements for the Award of the Degree of

Doctor of Philosophy

by

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October 2021

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Declaration by the Student

Date: October 4, 2021

Title of the Thesis: **Design and Analysis of Compact MIMO Antenna with Isolation Enhancement using CMA/Decoupling Techniques**

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Supervisor: Dr. Shrivishal Tripathi

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Abstract

The increase in demand for Multiple-input-multiple-output (MIMO) antenna facilitates the high data rate, channel capacity, and communication reliability. Now these days, the wireless communication system requires compact as well as high isolated MIMO elements. The compact design is easily integrable with portable mobile devices. The MIMO antenna design for small compact devices with high isolation is challenging compared to a larger structure. The Thesis aims to isolation improvement of MIMO antenna for compact devices using characteristics mode analysis (CMA) and decoupling circuit design techniques. The isolation improvement techniques of MIMO structure require more insight in terms of physical and analytical approaches. The CMA analysis helps to provide a more physical understanding of the structure, which allows achieving sound isolation in compact dimension MIMO antennas. The systematical isolation improvement technique is obtained using CMA analysis with the help of DGS. The novel vias-based stub decoupling processes is offered with the support of CMA, which can be used for different types of MIMO antenna.

Using a decoupling circuit design strategy for isolation improvement of MIMO antenna helps to achieve high isolation in closely coupled compact MIMO antennas. The multipath decoupling circuit-based design helps to improve the isolation of dual-band MIMO antenna, which can easily be extended into a multi-band design. The 2^{nd} and 4^{th} order-based decoupling circuits have presented the capability to isolate wideband MIMO elements in a close coupling scenario. The Hexagonal Split Ring Resonator (HSRR) enhances the isolation of wideband MIMO antenna in the next level with 2^{nd} order decoupling circuit. The MIMO antenna design for the mobile terminal for the 5G system required more compactness. The 5G devices needed at least eight elements of MIMO antenna. The self-decoupling techniques are explored to design a compact MIMO antenna; easily integrated into a 5G mobile system. The self-decoupled MIMO antenna is presented, and its easy extension of the element is also explored in this Thesis. The comprehensive solution is suitable for sub-6GHz 5G mobile devices.

The application of different isolation improvement techniques for MIMO antennas are proposed. Its examined the performances such as narrowband, dual-band, and wideband with high isolation and compact dimension. The performance and characteristics of these antennas are studied. All the MIMO antenna structures are fabricated on the FR4 substrate of dielectric constants 4.3 with 1.6mm thicknesses. It is validated experimentally that the proposed MIMO antenna structures are suitable candidates for compact portable applications.

Keywords: *MIMO, Antenna, CMA, decoupling circuit, isolation, self-decoupling.*

1. Introduction

MIMO is a modern wireless technology for increasing the capacity of the channel employing various transmit and receive antennas to realize multipath propagation [1], [2]. MIMO systems explicitly bring up an applied technique for transceiving numerous free channels concurrently over the same radio channel using multiple antenna technology deprived of any additional power loss. MIMO techniques [3] are used universally in advanced wireless systems, for instance, wireless local area network (WLAN) and long-term evolution (LTE). It is also a key enabler for next-generation wireless technology due to its ability to enlighten system reliability and improving channel capacity using multiple antennas [4]. The increase of elements is easy to accomplish on the base station side, but it is very challenging on the user terminal side (in mobile and handy devices). In practice, compact planar antennas are desired to easily integrate antenna radiators with other printed circuit board (PCB) components in handy devices. Furthermore, it is occasionally required that all the elements have similar radiation patterns, good impedance matching, and the same polarization. However, due to the integration of numerous closely packed antennas in a close proximate on a single device with limited space, mutual coupling between elements is high, leading to a poor antenna and system performance (low efficiency and channel gain) [5].

The foremost challenge of the MIMO antenna design in compact devices is to achieve low mutual coupling among antenna elements due to the necessity of high isolation in the MIMO systems. Mutual coupling is mainly due to the surface waves, coupling between the ports, and coupling due to radiation fields. The fundamental cause for the poor isolation of the MIMO antennas is that the ports of antenna elements have one shared ground. The surface currents are coupled from one port to another across the shared ground, increasing the coupling between these ports [6].

2. State of the Art: Numerous approaches are offered in the literature of MIMO antennas to increase the isolation is such as metamaterial, defected ground structure (DGS), neutralization line, and Electromagnetic Band Gap (EBG) [7-18]. In [7], narrow open-ended slots and space diversity is utilized to improve the isolation. In [8], isolation is enhanced using DGS in the ground plane of the structure. The vertical ground strip with EBG structure in the top plane is utilized to improve isolation among patch antennas [9]. The orthogonally arranged patch antenna is isolated using parasitic elements in the system [9]. In [10], the shorting stub achieves isolation, leading the current from the antenna element to the ground rather than another element. The MIMO antenna ground is etched, and DGS is created with a T-shaped stub to isolation enhancement [11]. In [12], the Complementary split-ring array (CSRA) is used to modify the amplitude and phase of the original coupling field and improve the isolation. Isolation is improved by loading a split-ring resonator (SRR) on the sides of each element [13]. The two metamaterial SRR divisions are placed to achieve isolation in the MIMO antenna [14]. The complementary slot coupled SRR is designed to steer the coupling in the structure [15]. In [16], the planar EBG structure is created by modifying the ground plane to isolate the antenna elements.

Several techniques are available to improve isolation between the antennas in UWB MIMO systems [17]–[26]. In [17], the inverted L-shaped slot is used in the ground plane to enhance the isolation between two monopoles. The MIMO antenna utilizes two half-hexagonal stubs used in the ground plane to enhance isolation and improve the UWB matching [18]. A rectangular vertical arm in the center of the wide slot in the ground plane is installed for isolation [19]. In [20], the orthogonal placement of elements provides adequate isolation without using any decoupling circuit. In [21], to improve isolation among the radiating elements of the UWB-MIMO antenna, elements are placed horizontally flipped along the *x*-axis, with a Sierpinski fractal slotted structure is designed in the ground plane. The identical

antenna elements are placed orthogonally and cut from the lower edge of the dielectric substrate to obtain significant inter-element isolation [22]. In [23], two capacitive coupled decoupling stubs achieve sound isolation between antenna elements. The four-port MIMO antenna uses semi-elliptical monopoles to achieve the UWB band with DGS to improve isolation [24]. The compact Sierpinskiknopp fractal geometry-based UWB MIMO antenna is presented for isolation improvement in orthogonal arrangement [25]. In [26], the decoupling wall and neutralization network are utilized to improve the isolation. The decoupling fence is created with vias help, while the neutralization network is designed aided by short-circuited stepped-impedance structures.

3. Motivation and Objectives: MIMO antenna is used ubiquitously in modern telecommunication systems, such as LTE, Wi-Fi, WLAN, and 5G systems. MIMO antenna consists of more than one monopole nearby, which leads to mutual coupling among monopoles. The diversity performance is affected significantly due to mutual coupling between monopoles. Thus, the MIMO antenna with low mutual coupling in a compact dimension is desired to be integrated easily with external systems. MIMO antenna exploits the diversity techniques to enhance the transmission capacity, data rate, and reliability without increasing bandwidth and power consumption. However, integration of multiple antennas in small terminals is challenging, as the low isolation between closely spaced antennas degrades the system performances. The mutual coupling can seriously reduce the signal-to-noise ratio (SINR) of the adaptive antenna array [27], [28]. It may degrade carrier frequency offset [29], channel estimates [30], and angle of arrival [31]. The negative effect of low mutual coupling on the reflection coefficient of a MIMO antenna should not be underestimated [32]. So, the designing of a compact MIMO antenna with low mutual coupling is the major challenge. However, most of the above-presented works in [7-26] offer little explanations regarding physical insight, systematic design procedure, and analytical techniques for the MIMO systems isolation improvement. Therefore, the presented dissertation focuses on the possibilities of isolation enhancement techniques of MIMO antenna and suggests some associated solutions, including the research as mentioned above issues. The mutual coupling effect of the MIMO antenna is presented in Fig. 1.

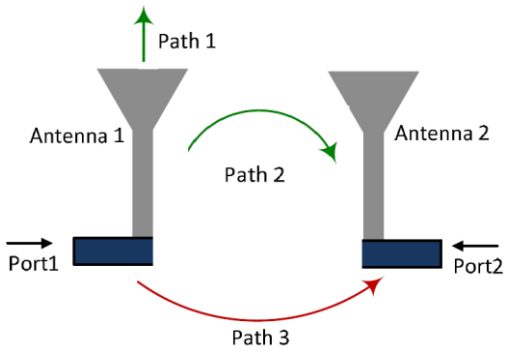

Fig. 1: Mutual Coupling effects on the MIMO antenna.

The objective of the Thesis is motivated by the points mentioned above are listed below:

1. To study the different isolation improvement techniques of MIMO antenna such as DGS, EBG, neutralization line, ground stubs, physical insight, orthogonal diversity, decoupling circuits, and self-isolation techniques.
2. To propose some systematic design techniques for isolation improvement using physical insight with the help of CMA designed for dual-band and ultrawideband (UWB) MIMO antenna.
3. To offer some novel method for isolation improvement by utilizing vias connected stub to steer the coupling current present in between antenna elements.

4. To provide some decoupling and matching circuit techniques to improve isolation for dual-band and wideband MIMO antenna.
5. To propose some self-decoupling MIMO antenna structure for advanced fifth-generation mobile systems using mixed-coupling tunning and internal inductive and capacitive tuning of MIMO elements.

4. Details of Research works:

4.1 Proposed Work Chapter 2: Systematic Design of MIMO Antenna

4.1.1 Systematic Design of Dual-band MIMO Antenna using CMA

This work uses characteristic mode analysis to design a dual-band (WLAN and Wi-Fi) MIMO antenna, as shown in Fig. 2. A step-by-step design procedure is discussed for a proposed structure using CMA modal significance. By analyzing Characteristic angle, eigenvalues, and modal importance in a systematic design approach, which help us to achieve good S11 (<-10dB) and S21 (<-15dB) in the desired bands. A single-band MIMO antenna is evolved in the presented work by identifying preferred resonating modes and undesired non-resonating modes using CMA. The chosen single band is achieved by tuning the non-resonating modes in the design. The presence of undesired non-resonating modes influences the mutual coupling between the antenna, and as a result, it diminishes the performance of the MIMO antenna. Defected Ground Structure (DGS) and stubbing in the ground plane are introduced to minimize the impact of mutual coupling. The proposed design shows a good envelope correlation coefficient (ECC), diversity gain, and Gain in the operating bands. The proposed MIMO antenna resonates at 2.4 GHz (Wi-Fi) and 5.5 GHz (WLAN) bands, as shown in Fig. 3(a). The diversity performance of the MIMO antenna is shown in Fig. 3(b). The ECC of the proposed design is less than 0.02, and the diversity gain is more than 9.95 in the operating bands. So the proposed design is a good candidate for small portable mobile and IoT devices.

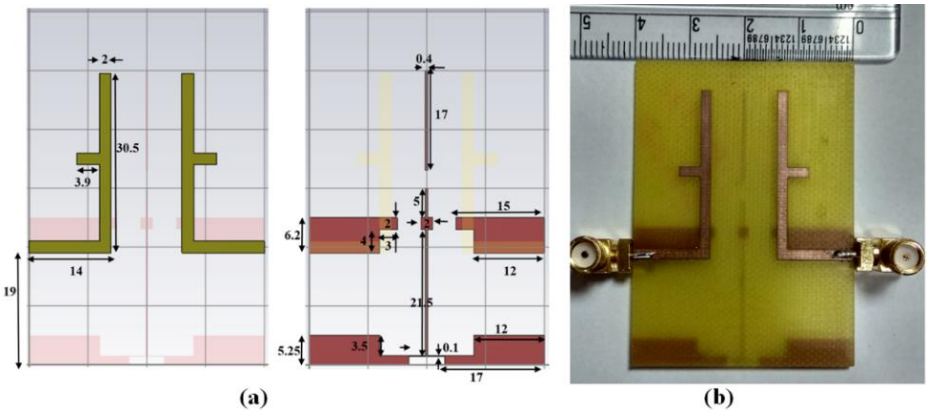

Fig. 2: Dual-band MIMO antenna (a) detail dimension, (b) fabricated prototype.

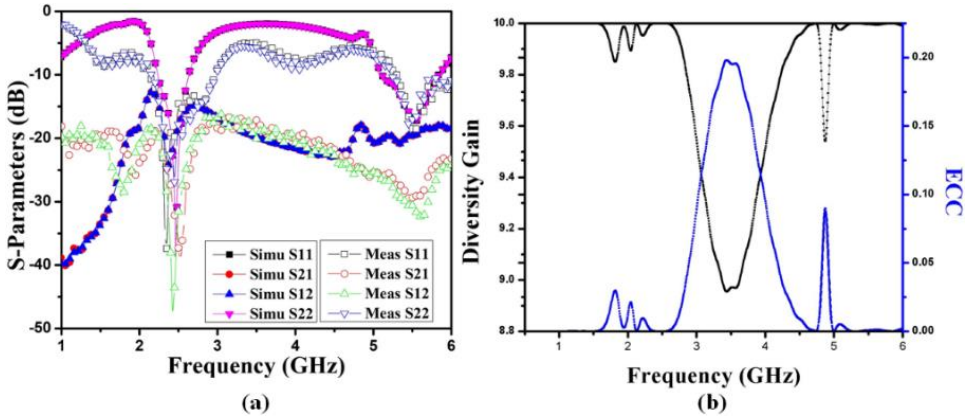

Fig. 3: Dual-band MIMO antenna (a) S-parameters, (b) diversity properties.

Compared with the other work, the proposed work has the following contributions:

1. Its systematic design approach helps design dual-band MIMO antenna using CMA.
2. The proposed work uses the concept of CMA modal significance to design MIMO antenna and reduce mutual coupling.
3. DGS is introduced to improve isolation by identifying a high coupling characteristic mode current.

4.1.2 Compact UWB MIMO Antenna with Cross-Shaped Unconnected Ground Stub using CMA

In this work, a compact ultrawideband (UWB) multi-input-multi-output (MIMO) antenna with a cross-shaped unconnected Ground stub using characteristic mode analysis (CMA) is presented. The proposed work consists of two elliptical shape monopole UWB antennas with a cross-shaped stub in the ground plane; the fabricated prototype is illustrated in Fig. 4. The compact MIMO antenna has a dimension of $25\times25\times1.6$ mm^3. These monopoles are able to excite several characteristic modes (CMs), which support wideband resonance, and cross-shaped stub support CM at lower frequency band in the ground plane and reduces mutual coupling between monopoles.

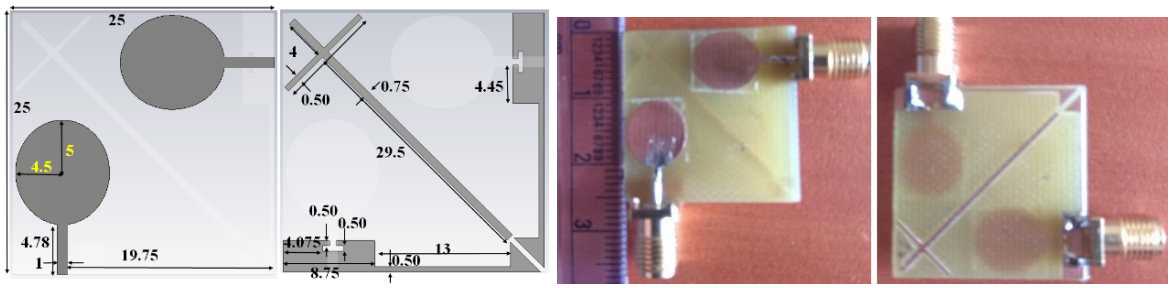

Fig. 4: Detail dimension of UWB MIMO antenna with the fabricated prototype.

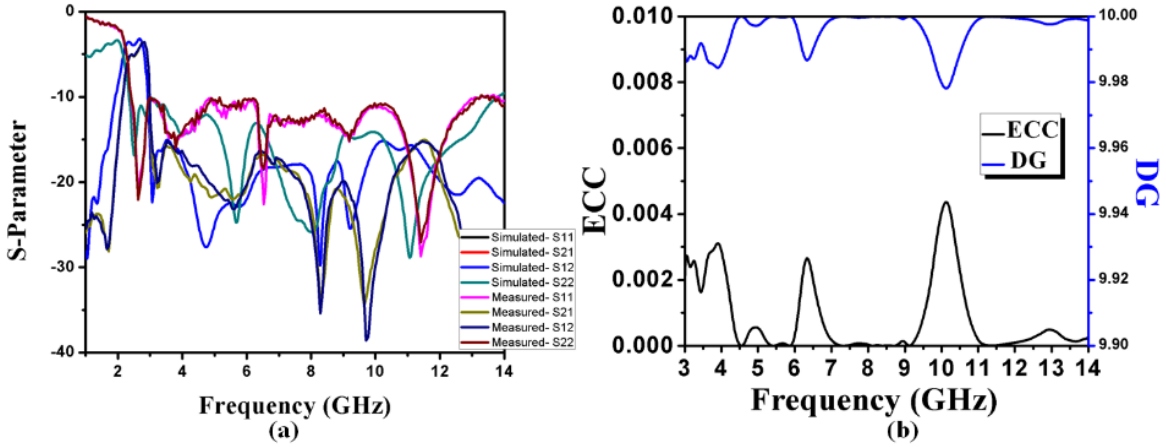

Fig. 5: UWB MIMO antenna (a) S-parameters, (b) diversity properties.

The UWB MIMO antenna resonates in frequency bands from 2.97 to 13.8GHz bandwidth with an excellent mutual coupling (<-15dB), as shown in Fig. 5(a). The diversity performance envelop correlation coefficient (ECC) and the antenna's diversity gain (DG) is less than 0.05 and more than 9.97, respectively, as illustrated in Fig. 5(b). The experimental result confirms a good treaty with the simulated ones so that the proposed antenna is suitable for compact UWB MIMO applications.

Compared with the other work, the proposed work has the following contributions:

1. The evolution of UWB MIMO antenna design is carried out by using CMA.

2. CMs are identified as a functional or nonfunctional mode; furthermore, it is tuned by observing modal significance and characteristic currents, which helps obtain a wideband response and low mutual coupling in the proposed structure.
3. In addition to that, a cross-shaped unconnected stub is introduced in the ground plan, which helps to achieve low mutual coupling.

4.2 Proposed Work Chapter 3: Isolation Improvement Technique using CMA through Vias-based Stub

4.2.1 Compact UWB MIMO Antenna with Fork-shaped stub with Vias Based Coupling Current Steering (VBCCS) to Enhance Isolation using CMA

This work has proposed a Fork-shaped stub with Vias Based Coupling Current Steering (VBCCS) to enhance the isolation between 2×2 and 4×4 ultra-wideband (UWB) MIMO antenna, as shown in Fig. 6 and 8. The proposed antenna is evolved using Characteristic Mode Analysis (CMA) to provide physical insight into the structure. The excitation of multiple characteristics modes facilitates the attainment of the UWB spectrum. The VBCCS with Fork-shaped stub-based methodology makes it possible to redirect characteristic current and enhance monopoles isolation. The antenna has an overall size of $20\times28mm^2$, covering the entire UWB spectrum from 3.01 to 13.5 GHz, keeping more than 17dB isolation, as shown in Fig. 7. The proposed UWB MIMO antenna presents an almost omnidirectional radiation pattern. Moreover, the diversity performance in terms of envelope correlation coefficient (ECC) < 0.01, and channel capacity loss (CL) < 0.04 b/s/Hz is analyzed. The proposed UWB MIMO antenna has a scalable phenomenon, and it can be easily extendable into 4×4 without any additional decoupling circuit. It operates from 3.05 to 13.05GHz frequency band with good antenna characteristics, as shown in Fig. 9. This work proposed a new methodology to achieve better isolation in a compact UWB MIMO antenna using CMA. In the design, 2×2 and 4×4 elements are placed symmetrically over the top layer of the substrate. The proposed work offers a compact solution for the UWB MIMO antenna. In this work, a Vias Based Coupling Current Steering (VBCCS) with a Fork-shaped stub is utilized to improve isolation. The presented two-element MIMO antenna is extended to a grander four-element by folding the element towards the structure's top side. To the best of the author's understanding, there is no work where it uses vias and stub to improve isolation within a compact dimension. Compared with the other work, the proposed work has the following contributions:

1. Its systematic design approach helps to achieve sound isolation (>17dB) in a given compact dimension, utilizing CMA.
2. The proposed work uses a new concept of coupling current steering using vias and Fork-shaped stub to enhance isolation among MIMO elements. In the design, VBCCS with Fork-shaped stub help in achieving better isolation on the compact MIMO antenna. It offers excellent isolation over a relatively broader bandwidth in a compact dimension.

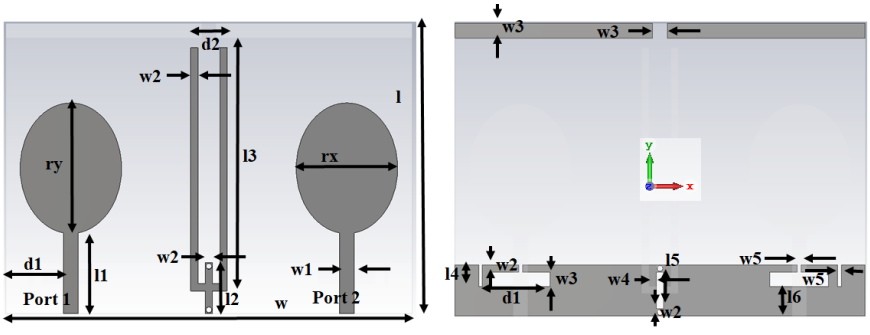

Fig. 6: Detail dimension of UWB MIMO antenna.

3. The proposed solution has a scalability phenomenon; its 4×4 UWB MIMO structure is achieved by simply folding the 2×2 UWB MIMO structure towards the top side without introducing any additional decoupling circuit.

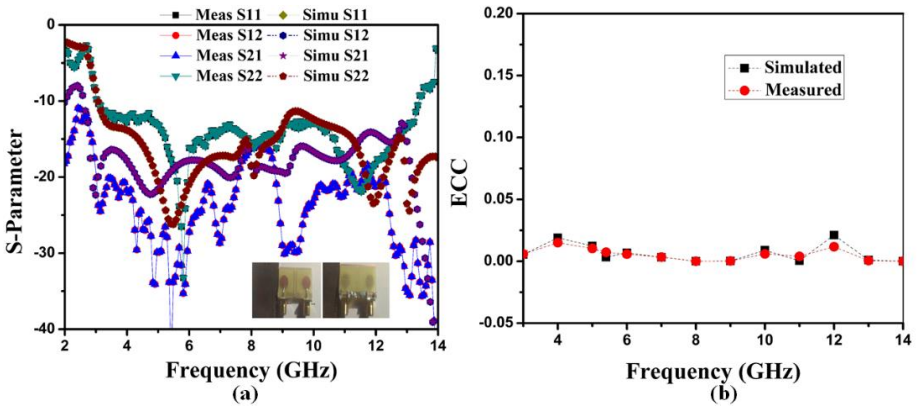

Fig. 7: Two-element UWB MIMO antenna (a) S-parameters results with fabricated prototype in the inset, (b) ECC.

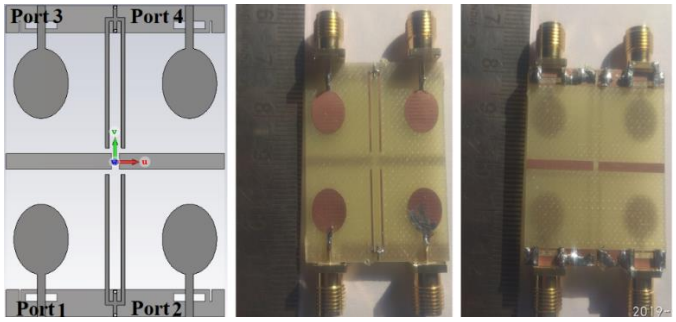

Fig. 8: Four-element UWB MIMO antenna structure with the fabricated prototype.

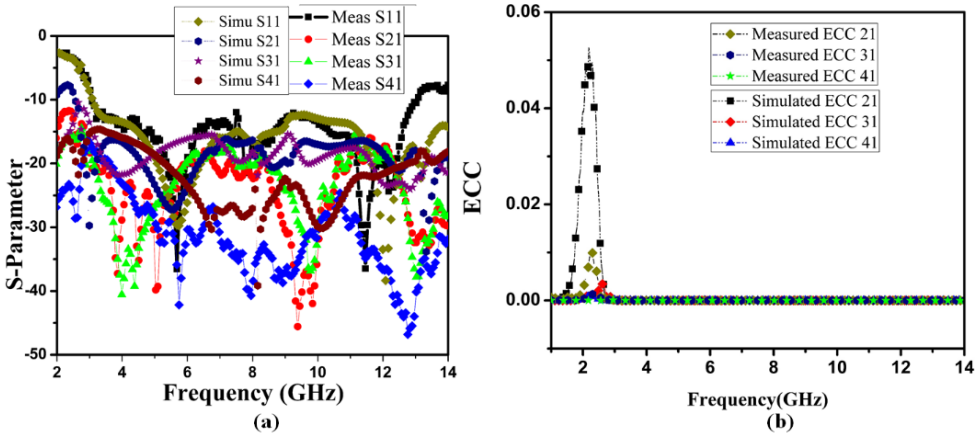

Fig. 9: Four-element UWB MIMO antenna (a) S-parameters results, (b) ECC.

4.2.2 Shared Ground Structure UWB MIMO Antenna Mutual Coupling Improvement using CMA

In this work, the mutual coupling improvement is achieved using Vias Based Coupling Current Steering (VBCCS), which is further supported by tilted Y-Shaped stub. The systematic design of the proposed UWB MIMO antenna is implemented by using the CMA. The UWB bandwidth is achieved by the correlative performance of different modes in the entire frequency range. The mutual coupling behavior is analyzed by characteristic currents and modal significance properties of CMA in shared ground

structure. The proposed antenna used VBCCS based stub to direct the characteristic current and reduce the mutual coupling between monopoles. This work presents a shared ground orthogonally located compact UWB MIMO antenna design, as shown in Fig. 10. Compared with the other work, the proposed work has the following contributions:

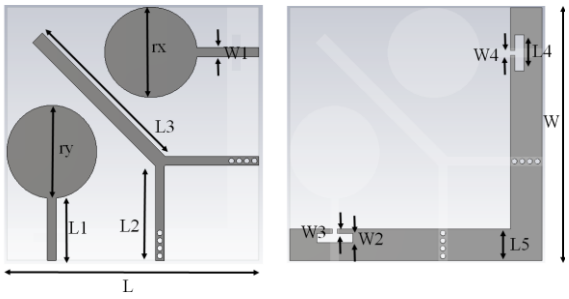

Fig. 10: Detail dimension of UWB MIMO antenna.

1. The evolution of UWB MIMO antenna design is carried out by using CMA.
2. CMs are identified as helpful for increasing mutual coupling among the elements.
3. In a compact dimension, the freedom of introducing DGS is limited due to space constraints in a shared structure. In the proposed design, we introduced two sets of Vias at an appropriate location to redirect characteristic current, which is involved in direct interaction between monopoles.

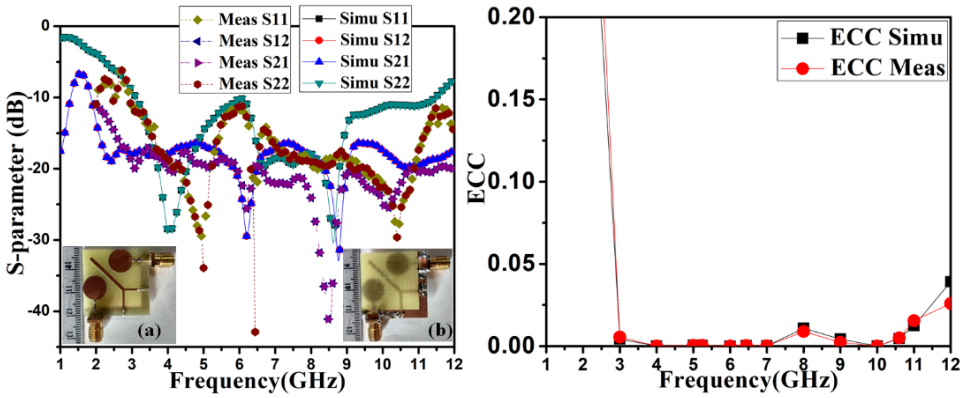

Fig. 11: UWB MIMO antenna S-parameter results with fabricated prototype and ECC.

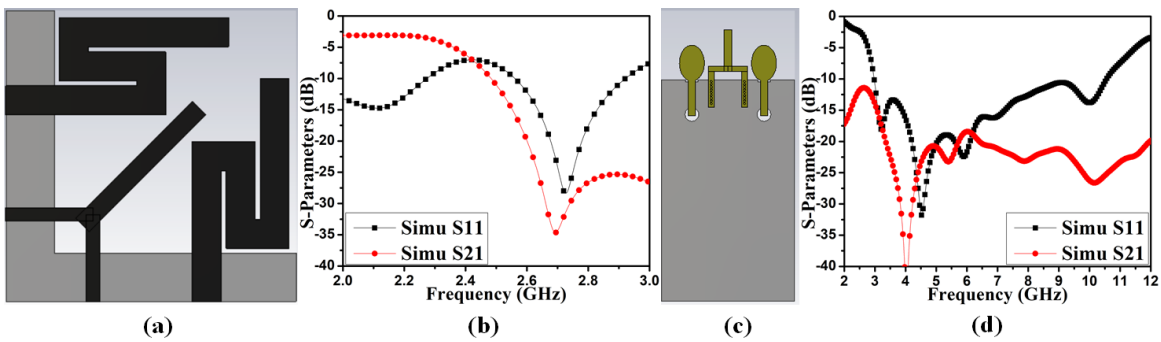

Fig. 12: Generalized MIMO antenna using similar decoupling (a) single-band MIMO antenna, (b) its s-parameter results, (c) UWB MIMO antenna with a large structure, (d) its structure s-parameters.

A Y-Shaped stub supports these Vias in the top plane to utilized the space and further support the circulation of characteristic current. The proposed work's contribution is that to reduce the mutual coupling in a compact dimension Vias based coupling current steering (VBCCS) with Y-shaped stub is realized using CMA. The Vias-based structure is a possible solution for mutual coupling reduction in a given compact dimension. The antenna has a compact size of 28 × 28 mm^2, which offers the UWB bandwidth from 3.05 to 11.5 GHz, with mutual coupling less than -17dB, as presented in Fig. 11. Moreover, it provides a nearly omnidirectional radiation pattern with envelope correlation coefficient (ECC) < 0.01, as illustrated in Fig. 10. The proposed decoupling technique is generalized for different antenna types such as single-band and large structure MIMO antennas, as presented in Fig. 12.

4.3 Proposed Work Chapter 4: Isolation Improvement Technique for Dual-band MIMO Antenna using Decoupling Circuits

4.3.1 Dual-band MIMO Antenna using Parallel Structure Decoupling Circuit

This work proposes a simple matching network and parallel structure decoupling circuits to improve isolation between dual-band antenna elements, as shown in Fig. 13. The proposed dual-band matching network provides good impedance bandwidth in both the bands of the MIMO antenna. However, the isolation between elements is still poor, enhanced using a simple dual-band decoupling circuits structure. The proposed MIMO antenna is resonating at 5.2GHz (WLAN) and 8.74GHz (X-band) bands to validate the proposed decoupling circuit's effectiveness and demonstrate the design procedure, as presented in Fig. 14. The antenna is resonating from4.35-5.3GHz and 8.7-9.5GHz, with 5GHz and 9GHz resonant frequency in the respective frequency range, with the isolation of more than 20 dB in the desired band. The diversity performance of the MIMO antenna is presented in Fig. 14. The ECC is less than 0.02 at both the resonating bands. The C_{loss} of the proposed dual-band MIMO antenna is lower than 0.05.

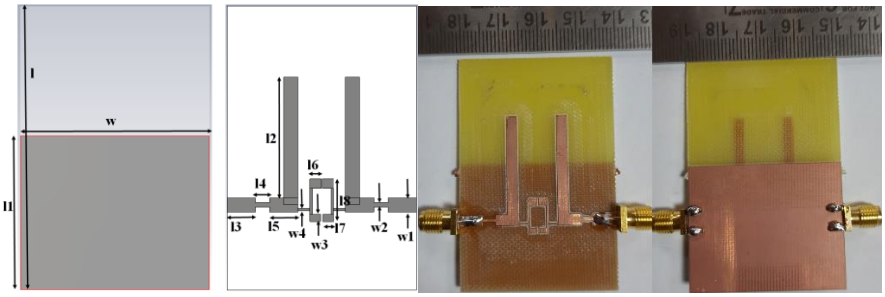

Fig. 13: Structure of Dual-band MIMO antenna with the fabricated prototype.

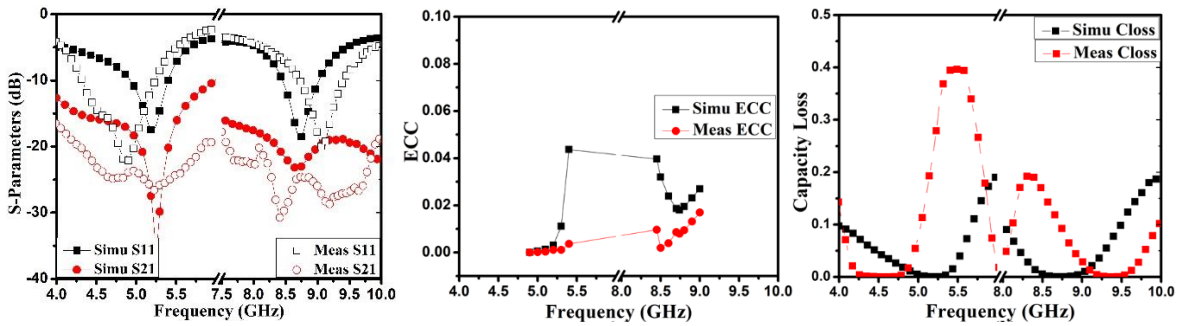

Fig. 14: Proposed Dual-band MIMO antenna S-parameter results and diversity performance.

4.3.2 Dual-Band MIMO Antenna Decoupling using Vias based Multipath Decoupling Circuit

This work offers a new decoupling circuit for isolation enhancement to decouple the dual-band multiple-input-multiple-output (MIMO) antenna in a compact dimension. In the design, a novel dual-band vias-based stub-loaded multipath decoupling circuit is used which offers multipath decoupling using admittance parameters of the structure to enhance isolation, as shown in Fig. 15. The vias position transforms the stub's behavior into a mix of inductive and capacitive behavior, and its diameter variation aids in isolation and frequency fine-tuning. The proposed multipath decoupling circuit helps to achieve good isolation between the antenna element using a hybrid coupling. The projected MIMO antenna simultaneously radiates at 2.29-2.51GHz (Wi-Fi) and 5.74-5.89GHz (WLAN) bands to validate the proposed decoupling circuit's effectiveness and demonstrate the design procedure, as presented in Fig. 16. The decoupling circuit helps obtain the isolation more significant than 20 dB in each band than the initial 11 dB in the Wi-Fi band and 14dB in the WLAN band. Moreover, the proposed decoupling scheme can be helpful for the redesign of other multi-band MIMO antennas applications. The excellent diversity performance makes this a suitable contender for advanced technological systems, as displayed in Fig. 16.

This work presents an original dual-band vias-based stub-loaded multipath decoupling circuit for isolation enhancement in a dual-band MIMO antenna. The multipath concept provides more accessibility to integrate with different bands. The design procedure of the decoupling circuit is expressed and analyzed thoroughly. The proposed decoupling circuit design is an efficient and simple structure for a dual-band MIMO antenna compared to existing work. It aims to provide sound isolation within a compact dimension. The works described in the literature and proposed in comparison to the decoupling method make the following contributions:

1. Compactness with good Isolation: The proposed decoupling circuit helps to achieve dual-band functionality with good isolation in a compact dimension.
2. Novel: The new vias-based stub-loaded multipath coupled resonator-based dual-band decoupling circuit is introduced to isolate the dual-band MIMO antenna. Moreover, vias-based stub offers a compact decoupling circuit suitable for MIMO antenna in a compact dimension.
3. Convenience: A relevant equivalent circuit model is projected to demonstrate the insight of this model. The multipath concept of decoupling circuit explained using an equivalent LC circuit of 2nd order (for higher frequency band) and 4th order (for lower frequency band). It helps to understand the dual-band isolation enhancement characteristic in the proposed vias-based decoupling circuit.

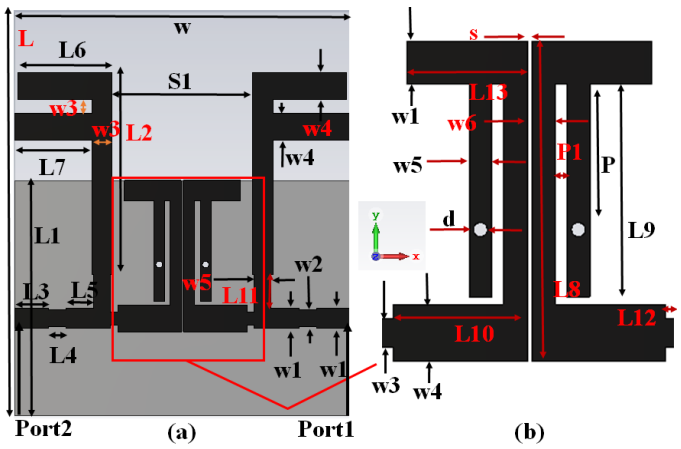

Fig. 15: Detail dimension of Dual-band MIMO antenna.

4. Reconfiguration: Due to the high degree of freedom provided by the proposed vias-based decoupling circuit, it has the flexibility of being modified for isolation improvement of MIMO antennas in a wide range of setups. The vias position changes the stub behavior into a combination of inductive and capacitive behavior, and its diameter helps to achieve fine-tuning in terms of isolation and frequency.

So, the proposed solution can be extended to a multi-band antenna. Furthermore, it can achieve high isolation for a single-band MIMO antenna using without a stub-loaded resonator.

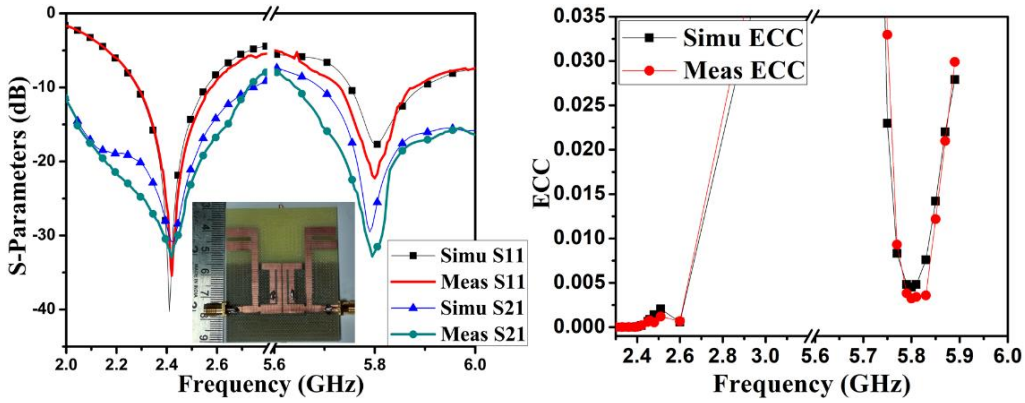

Fig. 16: Proposed Dual-band MIMO antenna S-parameter results and ECC.

4.4 Proposed Work Chapter 5: Isolation Improvement Technique for Wideband MIMO Antenna using Decoupling Circuits

4.4.1.1 Closely-Coupled MIMO Antenna with High Wideband Isolation using Decoupling Circuit

This work presents a design and modeling of a closely coupled MIMO antenna using a new simple wideband decoupling circuit based on a 2nd order filter for isolation improvement to decouple the dual-element/four-element wideband MIMO antenna array. The dual-element wideband MIMO antenna and the wideband decoupling circuit are designed using the structure's admittance parameter, as shown in Fig. 17. It is used further to extend the system for a larger array. The presented MIMO antenna is resonating at 5.12-5.9GHz (WLAN) bands, as shown in Fig. 18. The four-element wideband MIMO antenna is created using a back-to-back arrangement of dual-element MIMO antenna without any extra decoupling circuits, as presented in Fig. 19. The measured S-parameters of the proposed dual-element/four-element wideband MIMO antenna offer isolation (>20dB). The envelope correlation coefficient (ECC) is less than 0.04, along with good radiation characteristics, as shown in Fig. 18 and 19. This work offers a new decoupling circuit-based method for wideband isolation improvement between dual-element/four-element MIMO antenna array within a compact dimension. Compared with the other decoupling schemes, the proposed works have the following contributions.

1. A new useful and short wideband decoupling circuit is presented to decouple dual-element wideband MIMO antenna array in a compact dimension without any additional resonator for decoupling. It provides the proper analytical design strategy.
2. It offers sound isolation over a relatively broader bandwidth in a compact dimension.
3. The further extension of the antenna element is achieved by using back-to-back arrangements of dual-element MIMO structure. The decoupling circuit is effectively improving the isolation for the extended four-element designed structure as well.

4. The MIMO antenna demonstrates the flexibility to integrate with large structure PCB sheets. The antenna placement is independent of the location, shape, and PCB sheet size. The MIMO antenna's packaging features are shown by analyzing the extended ground effect and mobile housing.

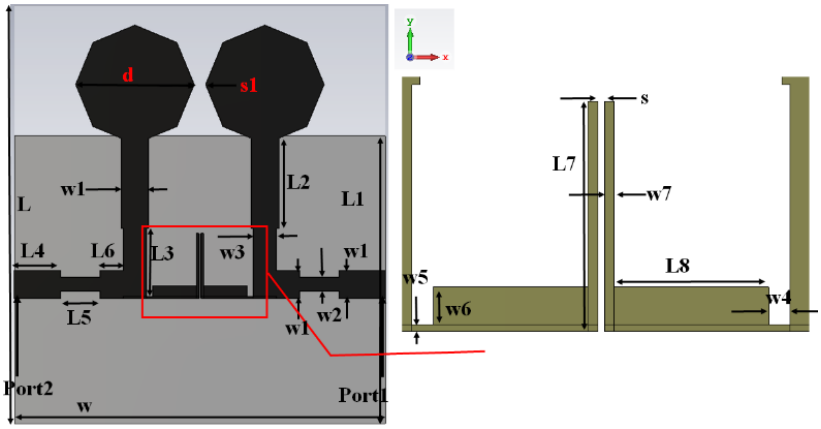

Fig. 17: Wideband MIMO antenna detailed dimension.

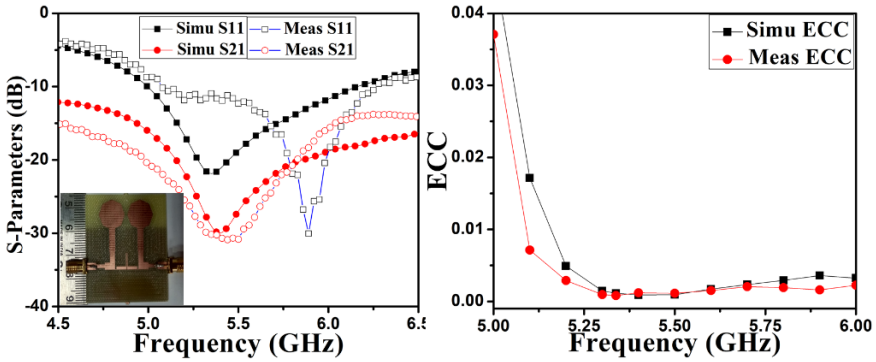

Fig. 18. The proposed dual-element wideband MIMO antenna S-parameters with diversity performance.

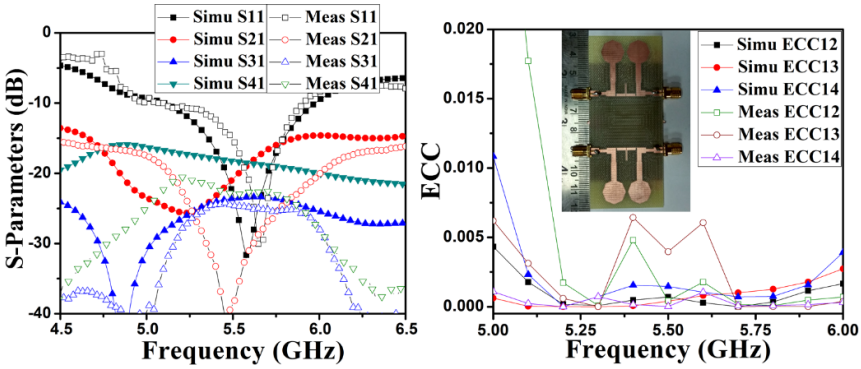

Fig. 19. The projected four-element wideband MIMO antenna S-parameters and ECC.

4.4.1.2 Closely-Coupled Wideband MIMO Antenna with Isolation Improvement using Decoupling Circuit and Hexagonal Split-Ring Resonators

This work presents a closely coupled wideband MIMO antenna design using a new simple wideband decoupling circuit (DCkt) based on a 2nd-order filter for isolation improvement to decouple the

wideband MIMO antenna array. The wideband closely-coupled MIMO antenna and the DCkt are designed using the structure's admittance parameter. Six hexagonal split-ring resonators are utilized to achieve good isolation in wide-bandwidth, as shown in Fig. 20. The presented closely-coupled wideband MIMO antenna is resonating at 5.08-6.30GHz (WLAN) bands, with measured isolation (>25dB) in the 5.12-5.98GHz frequency range, as illustrated in Fig. 21. The envelope correlation coefficient (ECC) is less than 0.1, along with good radiation characteristics, as presented in Fig. 21. It exhibits an unprecedented expansion, making the proposed solution the right candidate for advanced technological applications such as 5G and IoT.

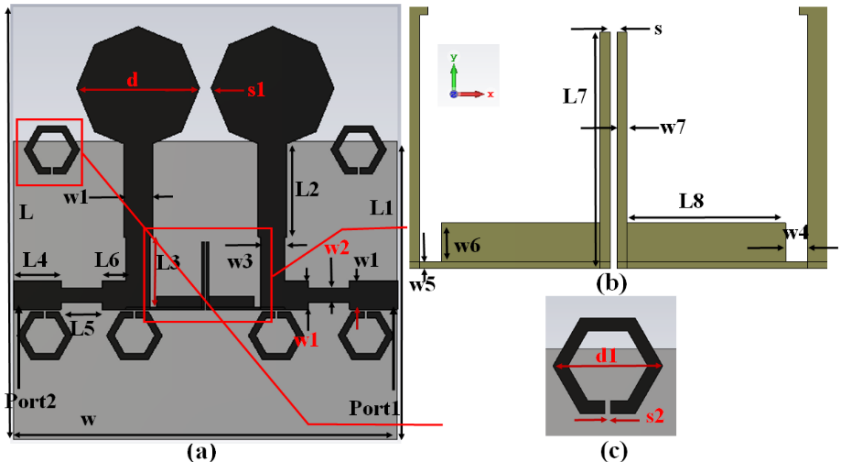

Fig. 20. MIMO antenna structure (a) optimized structure, (b) DCkt, and (c) HSRR.

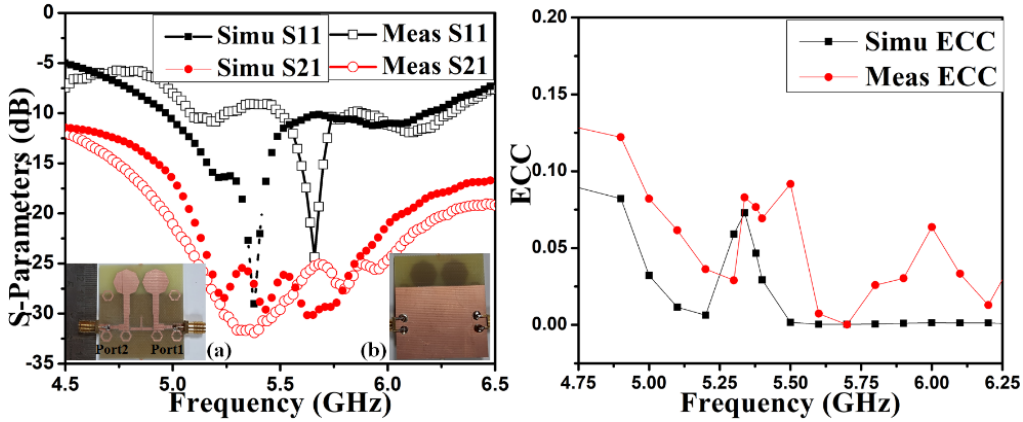

Fig. 21. Proposed MIMO antenna S-parameters (the fabricated prototype is in inset (a) front view, (b) back view), with ECC.

This work proposes a new DCkt and Hexagonal-shaped SRR (HSRR) based method for wideband isolation improvement between closely coupled MIMO antennas within a compact dimension. To improve the isolation further, six HSRR is placed to enhance isolation further in a wideband sense. The proposed decoupling work contrast with the other decoupling schemes, having the following influences.

1. The new wideband DCkt is offered to isolate wideband MIMO antenna elements deprived of any other resonator for isolation. It provides the proper analytical design strategy.
2. It offers high isolation over a relatively broader bandwidth in a compact structure.
3. The advanced extension of the MIMO antenna element improves isolation in the higher range by placing six HSRR in the appropriate structure location. The DCkt and HSRR are excellently improving the isolation for the two-element MIMO design.

4.4.2 Wideband MIMO Antenna Isolation Enhancement Using 4th-order Cross-Coupled Decoupling Circuit

This work presents a new fourth-order stub-based decoupling circuit for isolation improvement in a wideband multiple-input and multiple-output (MIMO) antenna array. The proposed decoupling circuit uses a fourth-order coupling-resonator filter effect and is designed using the structure's admittance parameter. In the decoupling circuit design, finite transmission zeros provide cross-coupling, which helps to maintain admittance slope and reduce coupling among MIMO elements. Additionally, to demonstrate the proposed decoupling circuit concept's influence in achieving good wideband isolation in a compact dimension, octagonal and circular-shaped patch MIMO antennas are analyzed. The proposed decoupling circuit design impact analyzed by keeping edge-to-edge separation between MIMO elements is at a minimum of 0.2mm ($0.0035\lambda_0$ at 5.4GHz, WLAN band). This demonstrates that the decoupling circuits are antenna-independent and can be applied to other MIMO antennas, as shown in Fig. 22. The measured S-parameters of the proposed wideband MIMO antenna presents high isolation (>20dB) between the antenna elements, as shown in Fig. 23. Moreover, the proposed solutions' radiation behavior and diversity performance are evaluated, as displayed in Fig. 24. It demonstrates good properties that make it a suitable contender for advanced scientific applications. Compared to former decoupling systems, the proposed design provides a compact size broadband decoupling with contributions.

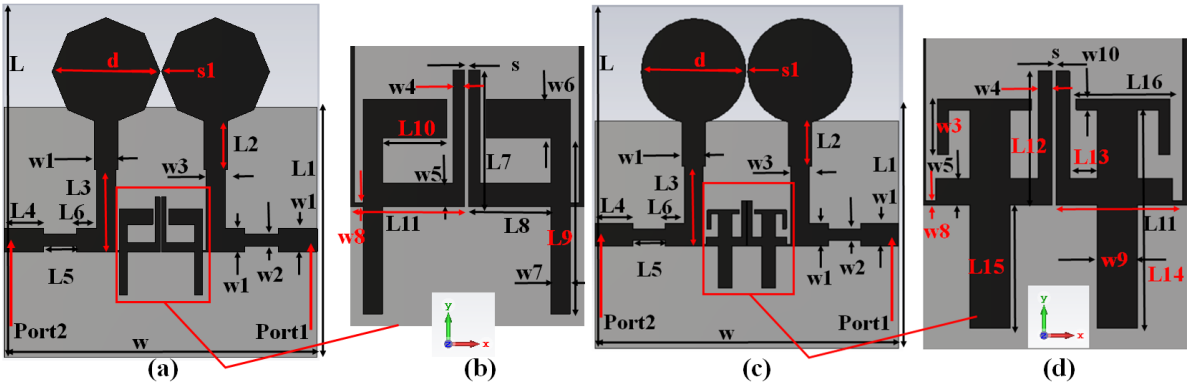

Fig. 22. Wideband MIMO antenna structure Octagonal-shaped (a) MIMO antenna, (b) decoupling circuit, Circular-shaped (c) MIMO antenna, (d) decoupling circuit.

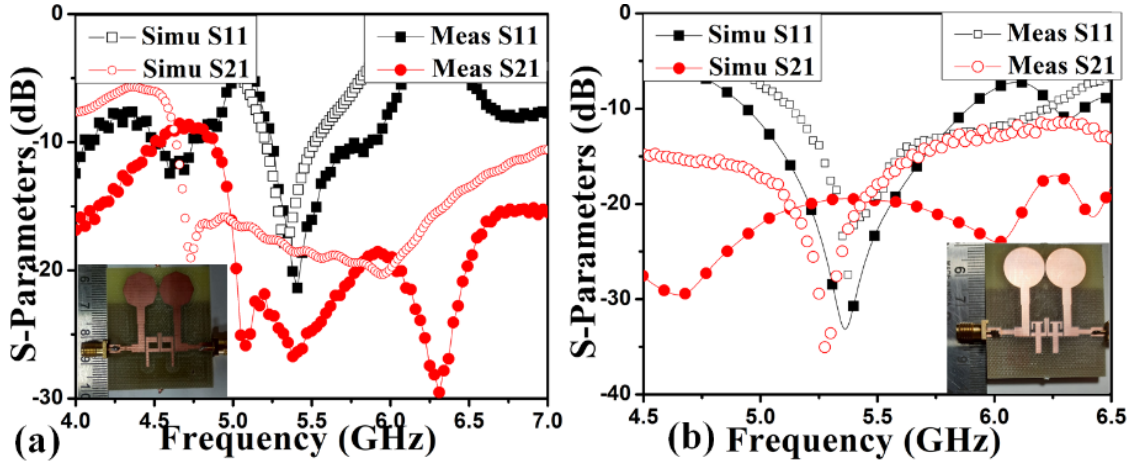

Fig. 23. The proposed MIMO antenna S-parameters (a) octagonal-shaped, (b) circular-shaped (fabricated prototype in inset).

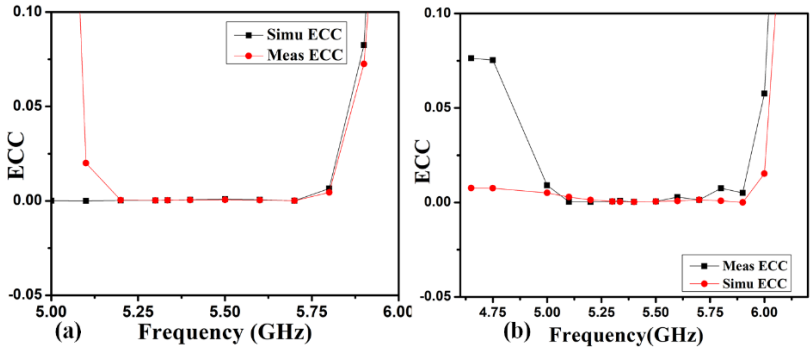

Fig. 24. The proposed MIMO antenna ECC (a) octagonal-shaped, (b) circular-shaped.

1. The new 4th-order cross-coupled decoupling circuit is offered to isolate a wideband tightly-coupled MIMO antenna in a dense aspect.
2. The finite transmission zeros (TZ) provide cross-coupling in the decoupling circuit, which helps maintain admittance slope and reduce coupling among wideband MIMO antenna elements.
3. The fourth-order cross-coupled decoupling circuit can achieve wideband-decoupling performance by the combined effect of two dual-band second-order circuits. The stopband in between these bands provides wideband isolation using cross-coupling among them.
4. The decoupling circuit can accomplish excellent isolation >20dB in very close proximity of MIMO elements, where the edge-to-edge separation between the elements is around 0.2mm.

Moreover, octagonal and circular-shaped patch MIMO antennas characteristics are examined to validate the proposed fourth-order cross-coupled decoupling circuit impact in achieving good wideband isolation in a compact dimension.

4.5 Proposed Work Chapter 6: Isolation Improvement Technique for MIMO Antenna using Self-decoupling Circuits

4.5.1 Compact Tightly-Coupled Self-decoupled Vias-Based MIMO Antenna using Hybrid Tunning

This work offers a compact, tightly-coupled, self-decoupled vias-based multiple-input multiple-output (MIMO) antenna pair with a common ground for a 5G system. The projected design comprises modified T-shaped tightly-coupled antenna elements. It is effortlessly helping to achieve sound decoupling across the desired band without using any extra decoupling circuit between the elements. It is revealed that the structure of the self-decoupled MIMO antenna tunes the inductive and capacitive (hybrid) effect of elements, which helps to achieve decoupling of antenna elements, as shown in Fig. 25. A relevant equivalent circuit model for coupled and decoupled MIMO antenna is proposed to validate the insight operation of this proposed theory. The hybrid tuning among the MIMO antenna elements reduces the coupling effect mutually by modifying the antenna shapes. The proposed self-decoupled MIMO antenna pair demonstrates low mutual coupling of less than -15dB across the 5G NR frequency bands: n48 and long-term evolution (LTE) band 42/52 (3.2–3.6 GHz) with good diversity characteristics, as displayed in Fig. 26. Moreover, the one proposed design structure can offer dual-band self-decoupling features. The proposed structure provides 3.2-3.6GHz and 3.95-4.115GHz frequency bands with good diversity properties, as shown in Fig. 27. This structure can optimize further to achieve dual-band/ wideband resonance in the design. In this work, a new theory for MIMO antenna design called self-decoupling is proposed. Associated with the other MIMO antenna, the suggested works have subsequent contributions.

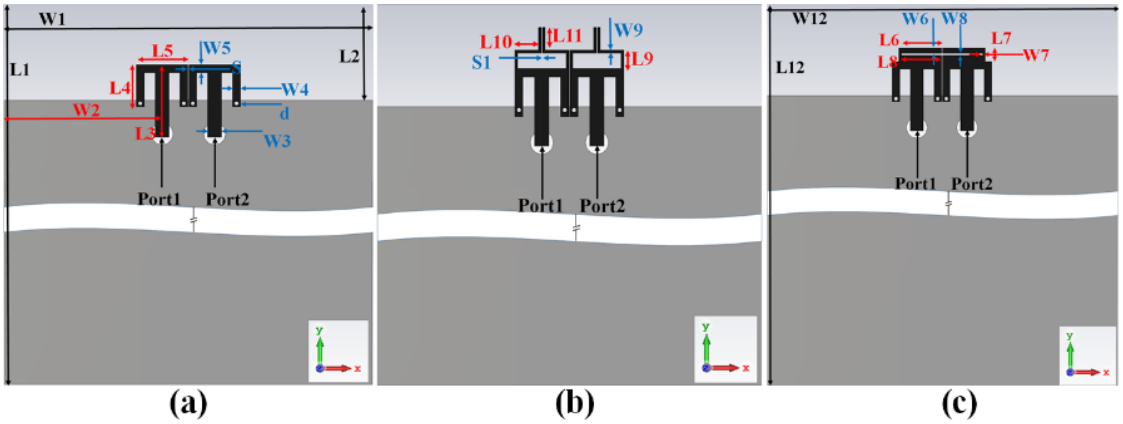

Fig. 25. Optimized design of tightly-coupled MIMO antenna structure with its examples (a) Cou, (b) DeCou1, (c) DeCou2.

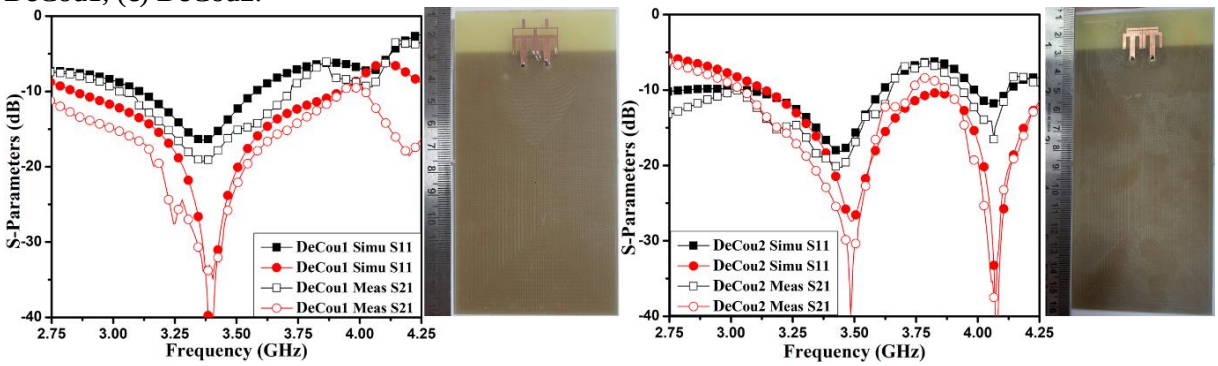

Fig. 26. The proposed self-decoupled MIMO S-parameter results along with the fabricated prototype.

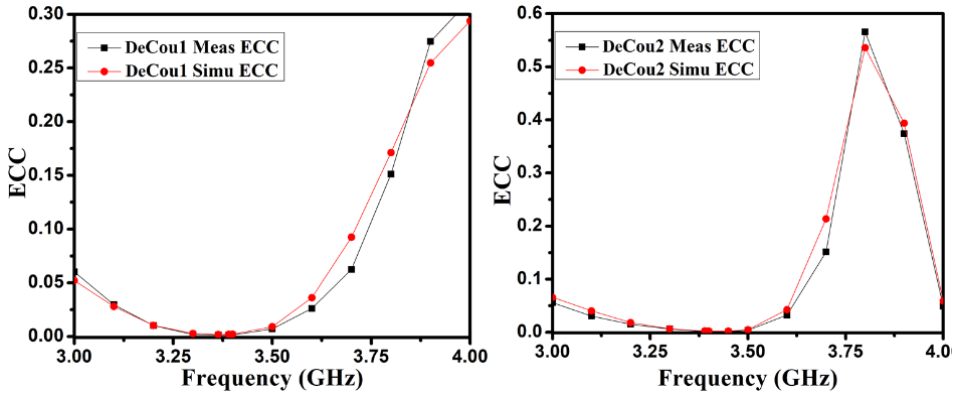

Fig. 27. The proposed self-decoupled MIMO ECC results.

1. The projected tightly-coupled vias-based MIMO antenna provides a self-decoupling phenomenon using inductive and capacitive tuning.
2. The essential idea is to equilibrium the antenna elements' inductive and capacitive (hybrid) effects to achieve decoupling.
3. The proposed structure can achieve dual-band self decoupled properties as well.
4. The self-isolation properties of the MIMO antenna offer isolations better than 15dB for both proposed designs throughout the operating band. The edge-to-edge separation between antenna elements is around 0.005λg (0.2mm) at 3.4GHz.

The proposed Decoupled MIMO antenna example1 can cover the 5G NR n48, LTE 42, and 52 bands at 3.5GHz (3.05-3.7GHz), and example2 can cover the frequency range 3.2-3.6GHz, and 3.95-4.115GHz, which are covered same LTE and 5G NR bands targeted for the upcoming sub-6GHz 5G band.

4.5.1 Self-Isolated MIMO Antenna using Mixed Coupling by Close Coupling Technique

In this work, a compact self-isolated multiple-input-multiple-output (MIMO) antenna with a shared ground is proposed for 5G systems. The proposed design consists of modified M-shaped, closely-coupled antenna elements. It is helping to achieve good isolation across the targeted bandwidth without using any extra decoupling structures. It is discovered that the arm of M-shaped antenna elements can cancel out the coupling on the system and achieve sound isolation among antenna elements. A relatable equivalent circuit model is discussed to demonstrate the insight operation of the proposed theory. The mixed couplings among antenna elements neutralize the coupling by correcting the antenna shapes. The proposed self-isolated 2-element MIMO antenna demonstrates sound isolation of superior to 15dB across the 5G NR frequency bands: n48/n78 and long-term evolution (LTE) band 42/43/48/52 (3.2–3.98 GHz), as shown in Fig. 28. Moreover, the proposed 2-element design structure has a scalability advantage. It is extended into an 8-elements structure, where a pair of antennas located at each side of the frame offers orthogonality. The proposed 8-elements M-shaped MIMO is validated using fabricated and simulated measurements, as presented in Fig. 29. The investigational results exhibit that the 8-elements MIMO system can provide better than 20dB isolation across the 5G NR frequency band n48 and LTE band 42/43/52(3.29–3.66 GHz), with sound diversity performance, as presented in Fig. 30. Related to the other MIMO antenna, the offered works have the following offerings.

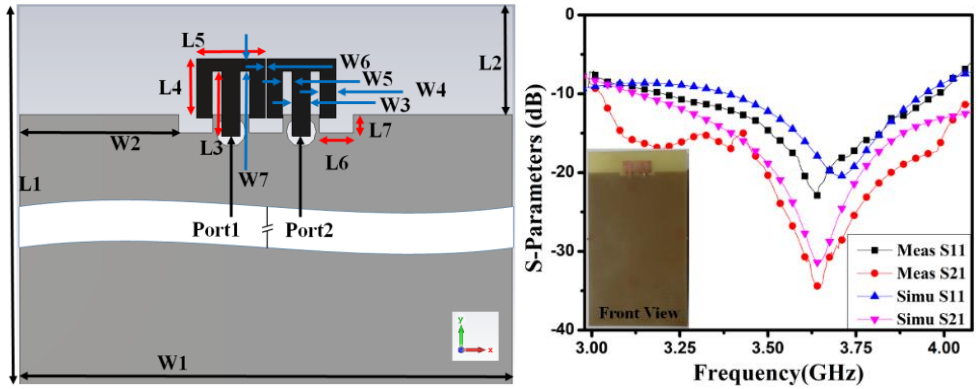

Fig. 28. Optimized design of self-decoupled MIMO antenna structure with measured S-parameters (fabricated prototype in inset).

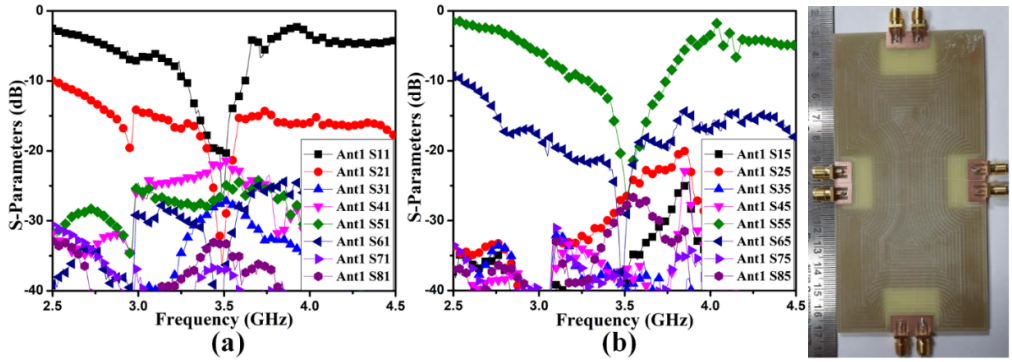

Fig. 29. Proposed 8 Elements MIMO antenna Measured S-Parameters (a) Ant 1, (b) Ant 5, with fabricated design.

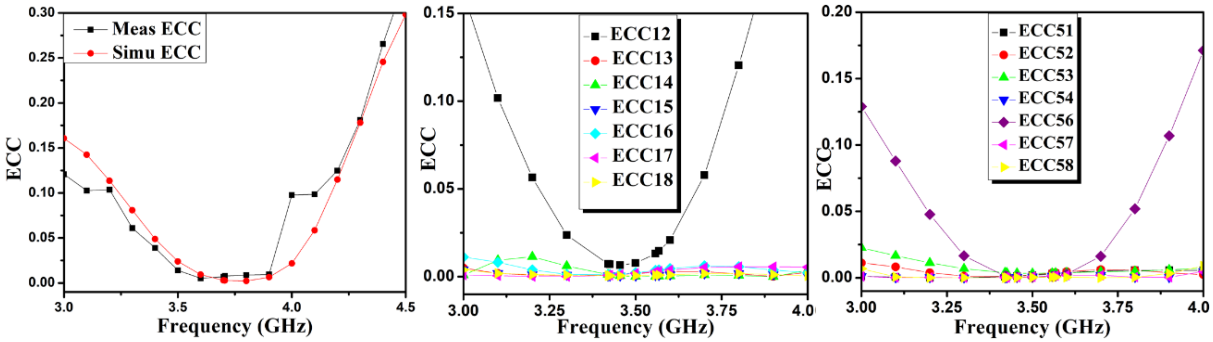

Fig. 30. Proposed Self-Decoupled MIMO antenna ECC results.

1. The proposed MIMO antenna structure provides a self-isolation phenomenon using a close coupling technique using mixed-coupling without any extra decoupling circuit with the nearby adjacent elements.
2. The central concept behind this is to balance the coupling among the antenna elements.
3. The proposed MIMO antenna elements are easily extended to more than a 2-element array due to the compactness and easily integrable of the proposed design structure.
4. The self-isolation properties of the MIMO antenna offer isolations better than 16dB for the 2-elements structure and 20dB for the 8-elements structure throughout the operating band. The edge-to-edge separation between antenna elements is around $0.005\lambda_g$ (0.2mm) at 3.8GHz.

5. Major Contributions of the Thesis:

Some of the significant contributions of the work are:

I. The systematic design approach for isolation improvement is proposed by using CMA by applying DGS. (a) Dual-band MIMO antenna, (b) UWB MIMO antenna.

II. The new decoupling approach is proposed for isolation improvement, which uses vias connected stub to steer the coupling current between the antenna elements.

III. Decoupling circuit design is proposed with the help of a vias-based multipath coupled-resonator for the Dual-band MIMO antenna, where vias provide us another degree of flexibility. The proposed approach can be extended to a multi-band MIMO antenna.

IV. Closely-coupled wideband MIMO antenna decoupling is achieved with the help of 2^{nd}–order decoupling circuit.

V. Closely-coupled wideband MIMO antenna decoupling is achieved with the help of 4^{th}–order decoupling circuit by utilizing a wide stop-band for high isolation.

VI. The projected tightly-coupled vias-based MIMO antenna provides a self-decoupling phenomenon using inductive and capacitive tuning. One of the proposed structures can achieve dual-band self decoupled properties as well.

VII. The proposed MIMO antenna structure provides a self-isolation phenomenon using a close coupling technique and a hybrid tuning technique without any extra decoupling circuit with the nearby adjacent elements.

6. Conclusion and Future Scope:

The importance of MIMO antenna in current and future wireless communication is well known. The MIMO antenna is supported to improves the channel capacity, data speed, and communication reliability. This work discovers the isolation improvement techniques among the MIMO elements practices, prospects, and challenges in compact and mobile devices. The main categories of isolation improvement, namely systematic design using CMA, vias-based stub, Decoupling Circuit for dual-band

and wideband, self-decoupling techniques using the hybrid tuning and close-coupling techniques, are explored to disclose their role and new possibility in the realization of MIMO antenna.

The future work objectives are to discover the compact MIMO antenna array design concerning the state-of-the-art design possibilities. Some of the future scopes are listed below:

1. UWB MIMO antenna with the help of decoupling circuit
2. Self-decoupled UWB MIMO antenna
3. Self-decoupled MIMO antenna array for advanced communication system

7. Organization of the Thesis:

The Thesis contains the following seven chapters.

I. **Chapter-1**: This chapter discusses the basic introduction and state-of-the-art MIMO antenna design. Apart from that, it consists of different isolation improvement techniques. The chapter covers different design strategies, problem definitions, proposed solutions, and analyses. Additionally, the inspiration behind the research work, aims, Thesis organization, and significant contributions have also been detailed. **Publications: [10]**

II. **Chapter-2:** This chapter offers systematic design techniques using CMA with the help of DGS. The work also highlights the significant contributions, systematic design strategy, problem origination, and results-based performance analysis. **Publications: [2] & [11]**.

III. **Chapter-3:** This chapter presents a new vias-based decoupling design to improve isolation. The work proposes novel influences, which are generalized for different types of MIMO antenna. **Publications: [1] & [3]**.

IV. **Chapter-4:** This chapter offers to decouple circuit-based isolation improvement Solutions. The work covers the analytical model for dual-band MIMO antennas. **Publications: [7] & [12]**.

V. **Chapter-5:** This chapter offers to decouple circuit-based isolation improvement solutions for wideband MIMO antennas. **Publications: [4],[5] & [6]**.

VI. **Chapter-6:** This chapter contains a novel self-isolated compact MIMO antenna design solution for the upcoming sub-6GHz 5G MIMO antenna. The work covers the analytical modeling for self-isolated MIMO antennas. **Publications: [8] & [9]**.

VII. **Chapter-7:** This chapter highlights the conclusion and future work. General summary, limitations, and related future work are incorporated in this section.

8. Publications from the Thesis

Patent Submitted:

[1] Harsh Verdhan Singh, and Shrivishal Tripathi, "A Miniaturized UWB MIMO Antenna With Improved Isolation Using Vias Based Coupling Current Steering And Y-Shaped Stub".

Published Journal(s):

[2] Harsh Verdhan Singh, and Shrivishal Tripathi, “Compact UWB MIMO Antenna with Cross-Shaped Unconnected Ground Stub using Characteristic Mode Analysis”, *Wiley Microwave and Optical Technology Letters*, https://doi.org/10.1002/mop.31792.

[3] Harsh Verdhan Singh, and Shrivishal Tripathi, "Compact UWB MIMO Antenna with Fork-shaped stub with Vias based Coupling Current Steering (VBCCS) to Enhance Isolation using CMA", *AEU Journal of Electronics and communication*, https://doi.org/10.1016/j.aeue.2020.153550.

[4] Harsh Verdhan Singh, Shrivishal Tripathi, and Akhilesh Mohan" Closely-Coupled MIMO Antenna with High Wideband Isolation using Decoupling Circuit", *AEU Journal of Electronics and communication*, https://doi.org/10.1016/j.aeue.2021.153833.

[5] Harsh Verdhan Singh, D Venkata Siva Prasad, Shrivishal Tripathi, and Akhilesh Mohan, "Closely-coupled Wideband MIMO antenna with Isolation Improvement using Decoupling Circuit and Hexagonal Split-Ring Resonators", *Wiley Microwave and Optical Technology Letters*, https://doi.org/10.1002/mop.32941.

Under Review Journal(s):

[6] Harsh Verdhan Singh, D Venkata Siva Prasad, and Shrivishal Tripathi," Wideband MIMO Antenna Isolation Enhancement Using 4th-order Cross-Coupled Decoupling Circuit", *IEEE Canadian Journal of Electrical and Computer Engineering*. **[Under Review]**

[7] Harsh Verdhan Singh, D Venkata Siva Prasad, Shrivishal Tripathi, and Akhilesh Mohan," Dual-Band MIMO Antenna Decoupling using Vias based Multipath Decoupling Circuit", *AEU Journal of Electronics and communication*. **[*Revision under process]**

[8] Harsh Verdhan Singh, D Venkata Siva Prasad, and Shrivishal Tripathi," Self-Isolated MIMO Antenna using Mixed Coupling by Close Coupling Technique", *IEEE Transaction on Antenna and Propagation*. **[Communicated]**

[9] Harsh Verdhan Singh, D Venkata Siva Prasad, and Shrivishal Tripathi," Compact Tightly-Coupled Self-Decoupled Vias-Based MIMO Antenna using Hybrid Tunning", *Nature Scientific Reports*. **[Communicated]**

[10] Harsh Verdhan Singh, and Shrivishal Tripathi, "Comprehensive Review of Characteristics Mode Analysis: Theory to Application", *Wiley Microwave and Optical Technology Letters*, **[Under Review]**

Published Conference(s):

[11] Harsh Verdhan Singh, Shrivishal Tripathi, and Ramesh Vaddi, "Systematic Design of Dual-band MIMO Antenna using Characteristic Mode Analysis", *UPCON 2018*, 2-4 Nov. 2018.

[12] Harsh Verdhan Singh, and Shrivishal Tripathi, "Dual-Band MIMO Antenna for WLAN and X-band with High Isolation using CRDN", in *URSI-RCRS biannual conference* hosted by INC-URSI (Indian National Committee for URSI (International Radio Science Union)) at IIT BHU from 12-14 February 2020.

References

[1] C. Oestges, M. Guillaud, and M. Debbah, "Multi-polarized MIMO communications: Channel model, mutual information and array optimization," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Mar. 2007, pp. 1057-1061.

[2] M. Sánchez-Fernández, E. Rajo-Iglesias, Ó. Quevedo-Teruel, and M. L. Pablo-González, ``Spectral ef_ciency in MIMO systems using space and pattern diversities under compactness constraints," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1637-1645, May 2008.

[3] C. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multielement antennas," *Bell Labs Tech. Journal*, vol. 1, pp. 41-59, 1996.

[4] L. Wang, G. Wang, and Q. Zhao, ``Suppressing mutual coupling of MIMO antennas with parasitic fragment-type elements," in *Proc. 46th Eur. Microw. Conf. (EuMC)*, 2016, pp. 1303-1306.

[5] H. Li, J. Xiong and S. He, "A Compact Planar MIMO Antenna System of Four Elements With Similar Radiation Characteristics and Isolation Structure," in *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 1107-1110, 2009, doi: 10.1109/LAWP.2009.2034110.

[6] M. Farahani, J. Pourahmadazar, M. Akbari, M. Nedil, A. R. Sebak and T. A. Denidni, "Mutual Coupling Reduction in Millimeter-Wave MIMO Antenna Array Using a Metamaterial Polarization-Rotator Wall," in *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2324-2327, 2017.

[7] S. Nandi and A. Mohan, "A Compact Dual-Band MIMO Slot Antenna for WLAN Applications," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2457-2460, 2017.

[8] H. T. Chattha, et.al., "Compact Multiport MIMO Antenna System for 5G IoT and Cellular Handheld Applications," in IEEE Antennas and Wireless Propagation Letters, doi: 10.1109/LAWP.2021.3059419.

[9] A. Khan, S. Bashir, S. Ghafoor and K. K. Qureshi, "Mutual Coupling Reduction Using Ground Stub and EBG in a Compact Wideband MIMO-Antenna," in IEEE Access, vol. 9, pp. 40972-40979, 2021.
[10] X. -T. Yuan, Z. Chen, T. Gu and T. Yuan, "A Wideband PIFA-Pair-Based MIMO Antenna for 5G Smartphones," in IEEE Antennas and Wireless Propagation Letters, vol. 20, no. 3, pp. 371-375, March 2021.
[11] W. Wang, Y. Wu, W. Wang and Y. Yang, "Isolation Enhancement in Dual-band Monopole Antenna for 5G Applications," in IEEE Transactions on Circuits and Systems II: Express Briefs.
[12] Gao, D, Cao, Z, Quan, X, Xu, C, Chen, P, "A complementary split-ring array for compact decoupling 2 × 2 circularly polarized antenna", Microw Opt Technol Lett. 2021; 63: 1294– 1303.
[13] A. Ramachandran, S. Mathew, V. Rajan and V. Kesavath, "A Compact Triband Quad-Element MIMO Antenna Using SRR Ring for High Isolation," in IEEE Antennas and Wireless Propagation Letters.
[14] Wang, C, Yang, X-S, Wang, B-Z, "A metamaterial-based compact broadband planar monopole MIMO antenna with high isolation", Microw Opt Technol Lett. 2020; 62: 2965– 2970.
[15] Ghosh, J, Mitra, D, "A technique for reduction of mutual coupling by steering surface wave propagation", Microw Opt Technol Lett. 2020; 62: 1957– 1963.
[16] Abdelgwad, AH, Ali, M, "Isolation improvement of a two-port PIFA for MIMO using a planar EBG ground", Microw Opt Technol Lett. 2020; 62: 737– 742. https://doi.org/10.1002/mop.32059
[17] A. Mohanty, S. Sahu, "High isolation two-port compact MIMO fractal antenna with Wi-Max and X-band suppression characteristics," *Int J RF MicrowComput Aided Eng*. 2019,09,e22021.
[18] R. Mathur, S. Dwari' "A compact UWB-MIMO with dual grounded CRR for isolation improvement," *Int J RF MicrowComput Aided Eng*. 2018, 07, e21500.
[19] S. Saxena, B. K. Kanaujia, S. Dwari, S. Kumar, R. Tiwari, "A Compact Dual-Polarized MIMO Antenna with Distinct Diversity Performance for UWB Applications," *IEEE Antennas and Wireless Propagation Letters,* 2017,16, 3096-3099.
[20] D. Sipal, M. P. Abegaonkar, S. K. Koul, "Easily Extendable Compact Planar UWB MIMO Antenna Array," *IEEE Antennas and Wireless Propagation Letters,* 2017, 16, 2328-2331.
[21] S. Bukkawar, V. Ahmed, "Compact slot-loaded ultra-wideband multiple-input multiple-output antenna with fractal-inspired isolator," *Int J RF MicrowComput Aided Eng*, 2019, e22036.
[22] DK Raheja, BK Kanaujia, S. Kumar, "Compact four-port MIMO antenna on slotted-edge substrate with dual-band rejection characteristics," *Int J RF MicrowComput Aided Eng,* 2019, e21756.
[23] SP Biswal, S Das, "A compact printed ultra-wideband multiple-input multiple-output prototype with band-notch ability for WiMAX, LTEband43, and WLAN system," *Int J RF MicrowComput Aided Eng. 2019*, 10.
[24] R. Gómez-Villanueva, H. Jardón-Aguilar, "Compact UWB Uniplanar Four-Port MIMO Antenna Array With Rejecting Band," *IEEE Antennas and Wireless Propagation Letters*, 2019,18,12,2543-2547.
[25] S. Rajkumar, Krishnasamy, T. Selvan, P.H. Rao, "Compact 4 element Sierpinski Knopp fractal UWB MIMO antenna with dual band notch," *Microw Opt TechnolLett.*, 2018, 60, 1023–1030.
[26] K. D. Xu, J. Zhu, S. Liao, Q. Xue, "Wideband Patch Antenna Using Multiple Parasitic Patches and Its Array Application With Mutual Coupling Reduction," *IEEE Access*, 2018, 6, 42497-42506.
[27] Q. Yuan, Q. Chen, and K. Sawaya, "Performance of adaptive array antenna with arbitrary geometry in the presence of mutual coupling," *IEEE Trans. Antennas Propag.*, vol. 54, no. 7, pp. 1991-1996, Jul. 2006.
[28] B. Wang, Y. Chang and Y. Sun, "Performance of the large-scale adaptive array antennas in the presence of mutual coupling," *IEEE Trans. Antennas Propag*., vol. 64, no. 6, pp. 2236-2245, June, 2016.
[29] Y. Wu, J. W. M. Bergmans, and S. Attallah, "Effects of antenna correlation and mutual coupling on the carrier frequency offset estimation in MIMO systems," *Int. Conf. Wireless Commun. Netw. Mobile Computing (WiCOM)*, Chengdu, China, 23-25 Sept. 2010.
[30] S. Lu, H. T. Hui, M. E. Bialkowski, et al., "The effect of antenna mutual coupling on channel estimation of MIMO-OFDM systems," *IEEE Antennas Propag. Society Int. Symp*., Honolulu, HI, Jun. 2007, pp. 1-4.
[31] H. S. Lui and H. T. Hui, "Mutual coupling compensation for direction-of-arrival estimations using the receiving-mutual impedance method," *Int. J. Antennas Propag*., vol. 2010, pp. 1-7, 2010.
[32] D. M. Pozar, "A relation between the active input impedance and the active element pattern of a phased array," *IEEE Trans. Antennas Propag*., vol. 51, no. 9, pp. 2486-2489, Sep. 2003.